Table 1. FreedomCAR Technical Targets: On-Board Hydrogen Storage Systems[a, b, c]				
Storage Parameter	Units	2005	2010	2015
Usable, specific-energy from H_2 (net useful energy/max system mass)[d]	kW·hr/kg (kg H_2/kg)	1.5 (0.045)	2 (0.06)	3 (0.09)
Usable energy density from H_2 (net useful energy/max system volume)	kW·hr/L (kg H_2/L)	1.2 (0.036)	1.5 (0.045)	2.7 (0.081)
Storage system cost [e]	$/kWe·hr net ($/kg H_2)	6 (200)	4 (133)	2 (67)
Fuel cost [f]	$ per gallon gasoline equivalent at pump	3	1.5	1.5
Operating ambient temperature[g]	°C	-20/50 (sun)	-30/50 (sun)	-40/60 (sun)
Cycle life (1/4 tank to full)[h]	Cycles	500	1000	1500
Cycle life variation[i]	% of mean (min) @ % confidence	N/A	90/90	99/90
Minimum and Maximum delivery temperature of H_2 from tank	°C	-20/85	-30/85	-40/85
Minimum full-flow rate	(g/sec)/kW	0.02	0.02	0.02
Minimum delivery pressure of H_2 from tank FC=fuel cell, I=ICE	Atm (abs)	8 FC 10 ICE	4 FC 35 ICE	3 FC 35 ICE
Maximum delivery pressure	Atm (abs)	100	100	100
Transient response 10%-90% and)%-0% [j]	Sec	1.75	0.75	0.5
Start time to full-flow at 20°C[k]	Sec	4	4	0.5
Start time to full-flow at minimum ambient[k]	Sec	8	8	2
Refueling rate[l]	kg H_2/min	0.5	1.5	2
Loss of useable hydrogen[m]	(g/hr)/kg H_2 stored	1	0.1	0.05
Permeation and leakage[n]	Scc/hr	Federal enclosed-area safety-standard		
Toxicity		Meets or exceeds applicable standards		
Safety		Meets or exceeds applicable standards		
Purity[o] (H_2 from storage system)		98% (dry basis)		

Useful constants: 0.2778kWhr/MJ, ~33.3kWhr/gal gasoline equivalent.

Footnotes to Table 1

[a] Based on the lower heating value of hydrogen and a minimum of 300-mile vehicle range; targets are for complete system, including tank, material, valves, regulators, piping, mounting brackets, insulation, added cooling capacity, and/or other balance-of-plant components.

[b] Unless otherwise indicated, all targets are for both internal combustion engine and for fuel cell use, based on the low likelihood of power-plant specific fuel being commercially viable.

[c] Systems must be energy efficient. For reversible systems, greater than 90% energy efficiency is required. For systems generated off-board, the energy content of the hydrogen delivered to the automotive power plant should be greater than 63% of the total energy input to the process, including the input energy of hydrogen and any other fuel streams for generating process heat and electrical energy. This is based on the DOE on-board target of 90% efficiency and the DOE off-board energy efficiency target of 70% for hydrogen produced from natural gas.

[d] Generally the 'full' mass (including hydrogen) is used, for systems that gain weight, the highest mass during discharge is used.

[e] 2003 US$; total cost includes any component replacement if needed over 15 years or 150,000 mile life.

[f] 2001 US$; includes off-board costs such as liquefaction, compression, regeneration, etc; 2015 target based on H_2 production cost of $1.50/gasoline gallon equivalent untaxed.

[g] Stated ambient temperature plus full solar load No allowable performance degradation from –20C to 40C. Allowable degradation outside these limits is TBD.

[h] Equivalent to 100,000; 200,000; and 300,000 miles respectively (current gasoline tank spec).

[i] All targets must be achieved at end of life

[j] At operating temperature.

[k] Flow must initiate within 25% of target time.

[l] 2015 target is equivalent to 3-5 minutes refueling time.

[m] Total hydrogen lost from the storage system, including leaked or vented hydrogen; relates to loss of range.

[n] Total hydrogen lost into the environment <u>as</u> H_2; relates to hydrogen accumulation in enclosed spaces. Storage system must comply with CSA/NGV2 standards for vehicular tanks. This includes any coating or enclosure that incorporates the envelope of the storage system.

[o] For fuel cell systems, steady state levels less than 10 ppb sulfur, 1 ppm carbon monoxide, 100 ppm carbon dioxide, 1 ppm ammonia, 100 ppm non-methane hydrocarbons on a C-1 basis; oxygen, nitrogen and argon can't exceed 2%. Particulate levels must meet ISO standard 14687. Some storage technologies may produce contaminants for which effects are unknown; these will be addressed as more information becomes available.

4. Basis for Targets:

Why new targets and new target levels?

The original DOE targets for hydrogen storage were well designed to promote scientific research in the critical area of hydrogen storage. Promising new technologies were nurtured under these targets, and meaningful improvements in existing technologies were achieved. The focus now swings from demonstrating possibilities to making commercially viable components and products. Logically there is a concomitant change from discovery-oriented targets to engineering-oriented targets, and target levels are increasingly driven by system needs and customer expectations. In addition, it is still not clear if an ICE or a fuel cell will be the power plant in a hydrogen fueled vehicle. Until a clear decision is reached, hydrogen storage must strive to serve either system. These targets are aggressive. They are not meant to extend what is known by another incremental step, rather they are a challenge to the industrial and scientific community to reach in innovative, even radical, new ways to achieve what the consumer expects: a hydrogen vehicle that does everything current vehicles do, at a similar cost, but with the social advantages of hydrogen.

Usable specific energy from hydrogen, net:

This is a measure of the specific energy from the standpoint of the total onboard storage system, not just the storage medium. The storage system includes interfaces with the refueling infrastructure, safety features, the storage vessel itself, all storage medium, any required insulation or shielding, all necessary temperature/humidity management equipment, any regulators, electronic controllers, and sensors, all on-board conditioning equipment necessary to store the hydrogen (compressors, pumps, filters, etc.), as well as mounting hardware and delivery piping. Obviously, it cannot be so heavy as to preclude use on a vehicle. Further, the fuel efficiency of any vehicle is inversely related to the vehicle's mass. If the intent is to create an efficient, and thus lightweight vehicle, and to have it meet all customer expectations in terms of performance, convenience, safety, and comfort, then the total percentage of the vehicle weight devoted to the hydrogen storage system must be limited. These targets lead to the ultimate goal of 300 mile range in such a vehicle by the year 2015, and are suitably discounted in earlier years based on the assumptions of the expected vehicle usage and customers for those initial vehicles. They are based on customer expectations, rather than on the capabilities of the current candidates for hydrogen storage. For reference, the total fuel system in a typical 3000 lb. gasoline-powered production vehicle, which, by the way, has a fuel capacity of 16 gallons and a resultant range (@ 27.5 mpg) of 440 miles, has a mass of about 63 kg (including 44.75 kg of fuel). The energy in that fuel totals (33.3 kW-hr/gal x 16 gallons =) 532.8 kW-hr, and the resultant specific energy is (532.8/63) = 8.46 kW-hr/kg. If the fuel system in the vehicle were to be reduced in size to provide only a 300-mile range, it would carry 10.91 gallons, have a mass of 48 kg (including the fuel), stored energy of (33.3 x 10.91 =) 363 kW-hr, and a resultant useable specific energy of (363/48 =) 7.6 kW-hr/kg net. Obviously, these targets include an expectation that vehicle and powertrain efficiency improvements will be forthcoming. Note that this target is highly dependant of the storage capacity. For example, on an equal energy basis, assuming the energy stored in 5 kg of hydrogen is the equivalent of 5 gallons of gasoline in the example production vehicle, this number becomes ((33.3 x 5) / 29 (the new, smaller fuel system mass with 5 gallons of fuel) = 5.75 kW-hr/kg net for the example vehicle. The target is in units of net useful energy in kW-hr per maximum system mass in kg. "Net useful energy" is used to account both for unusable energy (i.e. hydrogen left in a tank below minimum powertrain system pressure requirement) and for hydrogen-derived energy used to extract the hydrogen from the storage medium (i.e. fuel used to heat a hydride to initiate or sustain hydrogen release). "Maximum system mass" implies that all of the equipment enumerated above plus the maximum charge of hydrogen are included in the calculation. Reactive systems increase in mass as they discharge; in such systems the discharged mass is used. Although the gasoline tank in the above example contributes only about 18 kg to today's IC vehicle, it is clear that the system weight associated with storing 5 kg of hydrogen will be substantially higher. High-profile light duty vehicles with current fuel cell efficiencies of ~50% were used to estimate the targets below.

Usable, specific-energy from H_2 (H_2 mass/max system mass)	kW·hr/kg net	1.5	2	3

Usable energy density from hydrogen, net: This is also a measure of energy density from a system standpoint, rather than from a storage medium standpoint. As above, the on-board hydrogen storage system includes every component required to safely accept hydrogen from the delivery infrastructure, store it on board, and release conditioned hydrogen to the powerplant. Again, given vehicle constraints and customer requirements (i.e. aerodynamics for fuel economy, luggage capacity for people), the system cannot take up too much volume, and the "shape factor" that the volume occupies becomes important. Also, as before, any unusable fuel must be taken into account. The targets assume both increased vehicle efficiency and the ability to store hydrogen in volumes that are currently dedicated to systems that may not be required in a hydrogen-fueled vehicle (i.e. a catalytic converter or muffler). For reference, the current production vehicle described above (with a 16-gallon tank) has a total fuel system volume of about 85 liters (including tank with vapor space, filler tube, pump, filter, fuel lines, vapor canister, valves, and mounting straps), stored energy of 532.8 kW-hr, and a resultant usable energy density of about (532.8/85 =) 6.3 kW-hr/l net. Again, this number is sensitive to the quantity of fuel, and would become (363/63.4 (the new fuel system volume) =) 5.7 kW-hr/l net for that vehicle with the fuel system reduced in size to limit range to 300 miles. Further, for that vehicle with only 5 gallons of fuel capacity, the energy density becomes (166.5/39 (the volume of a 5-gallon fuel system) =) 4.3 kW-hr/l net. By contrast liquid hydrogen by itself has a density of 2.35 kWhr/L. The targets are in units of net usable energy in kW-hr per system volume in liters.

Usable energy density from H_2	kW·hr/L net	1.2	1.5	2.7

Specific storage system cost: This target refers to the total projected cost of the entire on-board hydrogen storage system, including all hardware and storage media, plus an amortized estimate for any components or media, which would have to be replaced for the system to demonstrate a useful life of 150,000 miles in a vehicle. It is understood that the onboard fuel storage system for a hydrogen fueled vehicle may never reach the low cost of a fuel system in a current production vehicle, but it is expected that the societal benefits of hydrogen vehicles, combined with potential cost offsets and improved vehicle and powertrain efficiencies, will justify these targets. The target is in units of (2003 US) dollars per kW-hr of usable energy capacity ("usable energy" has been previously defined). The use of constant dollars is to facilitate direct comparisons. For reference, the example current production vehicle would have a system cost of about $240 and a usable capacity of 363 kW-hr, for a resultant specific storage system cost of $0.66/kW-hr. Due to the way things current components are priced, and due to the need to include all functions, reducing the size doesn't save much money, and a 5-gallon system would work out to (230/166.5 =) $1.40/kW-hr net. Note that the cost of the *first* charge, equivalent to 5 kg of hydrogen (and any additional costs associated with the first charge such as preconditioning cost), is included in the specific storage system cost, regardless of storage method (e.g. high pressure tanks, chemical storage, metal hydrides, etc.).

Specific storage system cost	$/kW·hr net (2003 US$)	6	4	2

Fuel cost:
This target is meant to provide guidance for chemical storage systems that are regenerated off-board. It also includes costs for compression, liquefaction, delivery, chemical recovery, etc. as required. The cost of regenerating by-products must be considered in terms of the FreedomCAR fuel cost targets, which are as follows:

Fuel cost	2001 US$/ gallon equivalent (pump price)	3	1.5	1.5

Operating temp (solar load): The storage system must dependably store and deliver hydrogen at all expected ambient conditions. The operation range expands with time. This reflects the expectation that the limited demo fleets will experience a less severe subset of ambient conditions. As commercial sales begin the vehicles can be expected to experience the full range of conditions, and eventually will be expected by consumers to operate perfectly in any weather encountered. The units are degrees C. The notation (sun) indicates that the upper temperature is a hot soak condition in full direct sun, including radiant heat from the pavement.

Operating ambient temperature	°C	-20/50 (sun)	-30/50 (sun)	-40/60 (sun)

Cycle life: Customers expect the fuel system to last the life of the vehicle, typically 150,000 miles. Assuming a 300mile range, that amounts to 500 full fill cycles. Many customers fill at partial capacity rather than at empty, requiring more fill cycles which implies more exposure to refill conditions and more time at the maximum fill level. Demo fleets may not require the customer expected durability, so 500 cycles is acceptable. Once wider sales start, 150000-mile life will be expected so an engineering factor is applied to ensure product reliability. At full fleet capability the risk increases and the engineering factor is raised to near that expected of gasoline. The units here are simply the number of cycles that must be demonstrated as a mean value. The cycle is defined as going from quarter full to full.

Cycle life (1/4 tank to full)[i]	Cycles	500	1000	1500

Cycle life variation: Manufactured items have item-to-item variation. The variation as it affects the customer is covered by the cycle life target;, the variation as it affects testing is covered in this target. It is expected that only one or two systems will be fabricated to test life of early concepts. The data generated has great uncertainty associated with it due to the low number of samples. Thus a factor is required to account for this uncertainty. The effect is to increase the required cycle life based on normal statistics using the number of samples tested. The value is given in the form XX/YY where XX is the acceptable percentage of the target life (90 means 90%), and YY is the percent confidence that the true mean will be inside the xx% of the target life (95 indicates 95% confidence or an alpha value of 0.05). For demonstration fleets this is less critical and no target is specified to functionally enable single specimen testing. Variation testing needs to be included for general sales. By the time full fleet production is reached testing levels will also need to tighten, but availability of multiple samples will no longer be a problem. This entire sequence is standard practice in the mass production of automobiles and their components. Units are in minimum percent of the mean and a percentage confidence level.

Cycle life variation	% of mean (min) @ % confidence	N/A	90/90	99/90

Minimum/maximum delivery temperature of H_2 from tank: Fuel cells currently operate between 80°C and 100C. If the temperature exceeds 100°C operation is unacceptable. In addition, if hydrogen enters above the cell temperature, this adds to the already significant water management and heat rejection problem. Thus, an upper limit on temperature is desirable. The value of 85 C is selected based on today's PEMFC technology. Over time, a higher value such as 100 C may be substituted because fuel cells are likely to operate at increasingly higher temperatures, and as the fleet size is increased, it will also become increasingly important that the storage system comply more closely with the fuel cell preferred operating range. The lower limits reflect both wider acceptance of fuel cells in varying climates and fuel cell improvements for lower temperature operation. The units are degrees C.

Delivery temperature of H_2 from tank	°C	-20/85	-30/85	-40/85

Minimum full-flow rate: This target is a measure of the maximum flow rate of hydrogen required by the powertrain to achieve the desired vehicle performance. It is based on an average 3000 lb. current production vehicle, which typically has a powerplant of about 150kW, but modified to account for FreedomCAR goal of 45% efficiency for a hydrogen-powered internal combustion engine. It is based on actual measured maximum gasoline fuel flow. This should not be considered only a transient phenomenon (though a vehicle would not accelerate through an entire tank of fuel, it might be called upon to tow a large, heavy trailer up an 18-mile grade, such as is found on Interstate 5 near Baker California). However, because fuel cell efficiency is poorest at full load, while ICEs are at or near their highest efficiency at full load, fuel cell vehicles will require the 2005 target level. Fuel cells are not likely to require the increase in this requirement with time. Several comments are in order here. These targets will ensure that, whatever the motive technology, the storage systems will be capable of meeting its requirements. Further, it protects for the possibility that IC engines powered by hydrogen may actually precede FC vehicles to market (and thus help to create a need for a hydrogen infrastructure). Second, this target is still quite limited, as it neglects the requirements of the ICE powered SUV/minivan/light truck segment, which currently makes up 50% of the market. Finally, this target is intended to indicate the potential for scalability for the hydrogen storage technology. This target is in units of mass/time normalized to powerplant size.

Minimum full flow	(g/sec)/kW	.02	.02	.02

Delivery Pressure (minimum acceptable): This target acknowledges that the onboard hydrogen storage system is responsible for delivering hydrogen in a condition that the powerplant can use. Since there can be no flow without a pressure differential, a minimum supply pressure is required just to move the hydrogen from the bulk storage to the powerplant. If the hydrogen were merely available at the entrance to a fuel cell, for instance, any pumps necessary to push or draw that fuel through the stack would be considered part of the fuel storage system. This is the only target that is different for fuel cells and for internal combustion engines. This is because the IC technology relies on pressurized fuel injection, and is envisioned to advance from low-pressure central or port injection to high-pressure in-cylinder direct injection by 2010. The units are in kilopascals and bar (roughly, standard atmospheres) absolute pressure.

Delivery pressure (minimum acceptable at full flow) FC=fuel cell, ICE = internal combustion engine	Atm (abs)	FC: 8 ICE: 10	FC: 4 ICE: 35	FC: 3 ICE: 35

Delivery Pressure (maximum acceptable): This target ensures that the on-board hydrogen storage system should not be designed such that extraordinary measures for pressure regulation are required before fuel is supplied to the fuel cell system.

Delivery pressure (maximum)	Atm (abs)	100	100	100

Transient response 10% to 90% and 90% to 0%: Transient response is one of the greatest challenges a vehicle powertrain faces. The storage system must track the needs of the fuel cell closely to provide adequate power and a suitable driving experience. The transient response is not symmetric. The 10 to 90% transient target is to meet the demand of the fuel cell or ICE during acceleration. The 90 to 0% transient reflects the fact the fuel cell can stop using hydrogen almost instantly and the fuel supply must stop quickly enough to avoid overpressuring any part of the system. . This parameter impacts performance, fuel cell durability, and vehicle control. The units are seconds to change between 10% flow and 90% flow, or 90% flow and no flow.

Transient response 10% to 90% and 90% to 0%	Sec	1.75	0.75	0.5

Start time to full-flow at 20°C:
The vehicle may be able to start based on hydrogen in the lines, but to maintain adequate function without the need for a second energy storage medium (batteries), full flow must be available almost instantly. Customers are currently accustomed to sub second start times. And full power available on demand any time after the key is released. The units for this target are seconds after start. Early demo fleets may not require starting times that rival current ICE technology, so a longer time is allowed. However, once large-scale production is started a value near that of an ICE is given. This need not mean the storage system must start in 0.5 second, only that fuel is delivered at max flow if requested. A small, moderate pressure buffer could serve to lengthen the true start up time. The mass and volume of the buffer would be charged against the system mass and volume. In addition, the storage system must provide some flow to the powerplant within 25% of the time target for full-flow.

Start time to full flow at 20°C	Sec	4	4	0.5

Start time to full-flow at minimum ambient:
See Start time at 20°C. The longer times reflect current customer expectation that in cold weather starting is more difficult. It is important to note that batteries are at their worst power capabilities at very low temperature. If a battery assist were contemplated, the battery system would likely have to be sized based on this starting condition, and thus would be rather large. This is why it is desirable to avoid batteries if possible. Consistent with the above target, some flow will be required to the powerplant within 25% of the full-flow target time. Units are in seconds.

Start time to full flow at min ambient	Sec	8	8	2

Refueling rate: Consumers expect to refuel a vehicle quickly and conveniently, especially on extended trips. The filling target is a rate, which allows a longer fill time for larger storage tanks (typically found on larger vehicles), and parallels the current customer experience. Currently, gasoline vehicles are filled in about 2-5 minutes, with small vehicles taking less time and large ones more time. Based on the expected efficiency of fuel cell vehicles, a minimum of 5kg of hydrogen will be needed for most vehicles. The long-term goal is to achieve near parity with current gasoline filling times. Demo fleets could operate with longer fill times, and initial commercial sales, probably in smaller vehicles, may be possible with a fill time of about 1kg/min. The units are kg of hydrogen placed on board the vehicle per minute.

Refueling rate	kg H_2/min	0.5	1.5	2

Hydrogen loss: This target protects against loss of range after extended periods of rest, for example parking during a vacation. Demonstration fleets are not expected to operate extensively in the normal consumer cycle, and the owners are better prepared to deal with low fuel situations, thus a lower standard is required. Vehicles purchased by consumers will be expected to have minimal perceptible loss of range after a week or two of parking, similar to gasoline vehicles today. Because the targets are normalized to mass of hydrogen stored, this target protects all tank sizes equally. At a value of 0.1, a full tank will require more than a year to empty. The units are g/hr of hydrogen lost via all routes, per kg of hydrogen stored.

Loss of useable hydrogen	(g/hr)/kg H_2 stored	1	0.1	0.05

Permeation/leakage, toxicity and safety: These targets are of great importance because they deal with protecting the health and well being of the owner. These types of concerns are generally regulated by the government. Only the permeation and leakage target has a clear set of units, standard cc of hydrogen per hour. Permeation and leakage is differentiated from hydrogen loss in that hydrogen that leaves the storage system but is first transformed into another species (e.g. water, via catalytic oxidation in a vent line) is not included in permeation and leakage but would be included in hydrogen loss. Permeation and leakage thus pertains to the possibility of generating a combustible hydrogen-air mixture outside the storage tank. Toxicity covers the possibility of consumer exposure to the storage material in normal, or abnormal conditions, plus worker exposure during manufacture and assembly. Safety covers all the typical safety statutes including certification and operation of vehicles, manufacture, transport, dispensing of fuel, and end of life issues. In each of these categories, compliance with federal standards, and potentially state and local standards will be required.

Permeation and leakage	Scc/hr	Federal enclosed-area safety-standard
Toxicity		Meets or exceeds applicable standards
Safety		Meets or exceeds applicable standards

Purity:
Hydrogen must be relatively pure going to the fuel cell or system efficiency will be degraded, ICEs are much more forgiving, though an exhaust after-treatment system may not be. Units are in volume % on a dry basis. Even inert impurities can degrade performance by progressively diluting the hydrogen at the anode, and necessitating venting of the anode, including some of the stored hydrogen. See target table footnote for specific impurity levels. It is also assumed that impurities from the hydrogen source do not degrade storage system performance. In other words, the hydrogen output from the storage system should be able to meet purity targets without the need for a ≥99.99% hydrogen input.

Purity of H_2 from tank	% (dry)	98	98	98